University
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# Earth System Models

especially those of
Intermediate Complexity

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## Essential Earth System Processes
(on land and sea, and in the air)

♦ Plate tectonics & volcanic activity
♦ Weathering, erosion, sedimentation
♦ **Biological production, biogeochemistry and the carbon cycle**
♦ Radiation (absorption, reflection, emission...)
♦ Convection (mantle, atmosphere and ocean)
♦ Oceanic transport (heat, salt, water, nutrients...)
♦ Atmospheric transport (heat, water, $CO_2$, etc)
♦ **Hydrology (evaporation, precipitation, run-off...)**
♦ Ice: accumulation, ablation, transport
♦ Soils & Sediments (formation & erosion)

# EMICs : Earth (Climate) System Models (of intermediate complexity)

♦ What are they ?

♦ Where are we now ?
  • Examples
  • Overview

♦ Issues
  • Timescales, Structure & Purpose
  • Processes & Components
  • Dimensionality & Resolution
  • "Complexity"

♦ Where are we going ?

♦ GENIE

# Model types

♦ Conceptual/illustrative
  • to build & test general understanding
    • e.g. simplified box models

♦ experimental
  • to test mechanisms, evaluate processes, etc
  • to model general (not specific) system behaviour

♦ explanatory
  • to explain past events
    • (fitted to some data, tested on the rest)

♦ simulation & prediction
  • as realistic as necessary/possible
  • for "operational" use

♦ **N.B. The model is a working hypothesis**

## MIT Climate Modelling Initiative

**Table 1. Heirarchy of Models**

*1D Radiative-Convective Equilibrium Model*

*1D Radiative Convective Equilibrium Model with interactive hydrological cycle*

*2D Coupled Atmosphere-Ocean Box Models (Hemispheric and inter-hemispheric*

*MIT 2D Land-Ocean Climate Model*

*Coupled 1D Atmosphere, 3D Ocean Model*

*Coupled 2D Atmosphere, 3D Ocean Model*

*3D Atmospheric Model with simplified physics/low resolution coupled to 3D Ocean Model*

*Proposed new State-of-the-Art 3D Coupled Atmosphere/ Ocean General Circulation Model*

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## Examples of ESM's
### (not all EMICS !)

♦ Hadley Centre (HADCM3)
  • moderate resolution, 3D at 3.75° (atm) by 1.25° (ocean)

♦ MPI Hamburg (ECHAM/LSG)
  • 3D at 5.6°/5.6°

♦ Potsdam  (CLIMBER-2)
  • 2.5D at 10° (lat) by 52° (long)
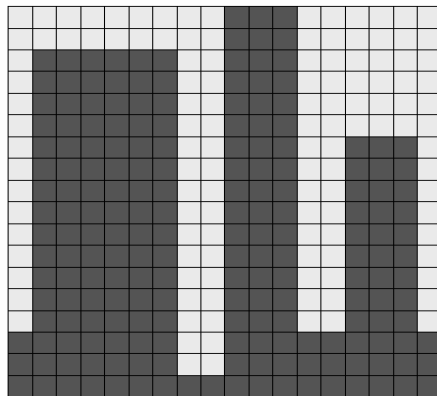
♦ Genie
  • 3D at 5° (lat) by 10° (long)

# CLIMBER-2
Ganopolski et al, Climate Dynamics (2000)
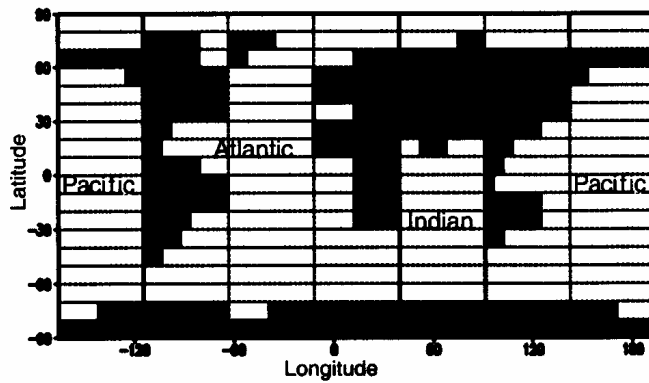


**Fig. 1** Representation of the Earth's geography in the model. *Dashed lines* show atmospheric grid, *solid lines* separate ocean basins

# "Lego-box" model layout
(Edwards & Shepherd 2001)



Figure 1: Diagram of the model domain, ocean cells are shaded dark grey. See text for explanation.

## Reasons for wanting intermediate complexity (2D, 2.5D & 3D ) models

♦ to allow for spatial variation
- include meridional transport of heat, water, etc ...

♦ to treat radiation (etc) explicitly
- include vertical transports of heat, water, etc...

♦ need to represent both **latitude** & **altitude**
- transport both by MMC and turbulence (eddies)
  - (MMC = mean meridional circulation)

♦ also : heat & water transport by ocean
- primarily due to **meridional** circulation

♦ Representation of continents & land surface…
- The zonal dimension is also important !

## What is an Earth System Model ?
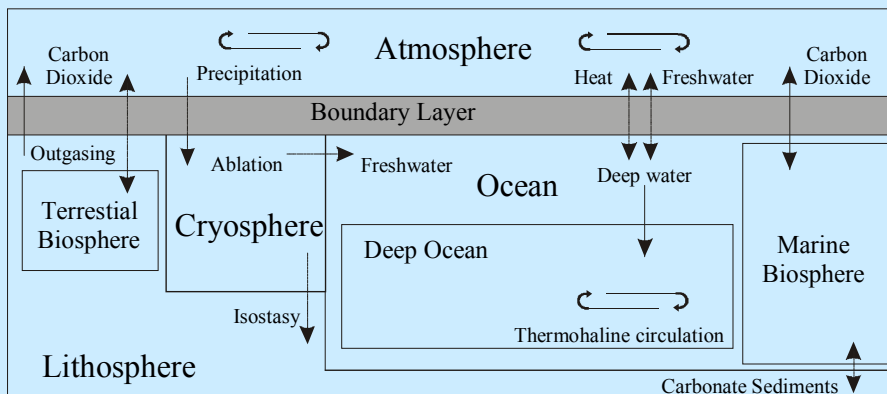
# Components of an ESM
## (for the Climate System)

♦ Oceans

♦ Atmosphere

♦ Continents (configuration)

♦ Land and sea surfaces (albedo)

♦ Biosphere : marine and terrestrial vegetation

♦ Cryosphere : ice sheets and sea-ice

# Earth System Models
## Processes & Timescales

| Time-scale (years) | Planetary | Continents | Land | Sea | Atmosphere | Ice | Biosphere |
|---|---|---|---|---|---|---|---|
| Billions | Solar evolution | Formation & Accretion | Erosion & deposition | Formation & Evolution | Formation & Oxygenation | Snowball Glaciations ?? | Origin of Life, "Mostly bacteria" |
| ~1e8 | | Continental Drift | Colonisation by plants | Basin formation | | Mostly warm & ice-free | Plants & animals |
| ~1e7 | | Volcanic episodes | Mountain building | Sediment accumulation | | Episodic Glaciations | Mass extinctions |
| Millions | | Crustal weathering | | Chemistry (calcium) | | Polar ice-caps | Species extinctions |
| ~1e5 | Insolation (Eccentricity) | | | Sea-level changes | | Glacial cycles | |
| ~1e4 | (Obliquity & precession) | | | Chemistry (phosphate) | | Last glacial to Holocene | |
| Thousands | Solar Variations ? | | | Thermo-haline circulation | Millennial (DO) Oscillations | | Eco-system evolution |
| ~100 | ditto | | | | Abrupt Climate Changes | | |
| ~10 | ditto | | | O-A Coupled Modes? | Decadal Modes? | | |
| ~1 | | | | | | Sea-ice variability | |

## Existing EMICS
Information from M. Claussen (PIK) et al

| Model | Institute | Dimension | | Total "Cells" | | M/C | CPU |
| | | Ocean | Atmos | Ocean | Atmos | type | (hours per kyr) |
| Bern 2.5D | Univ. of Bern | 2.5 | 1 | 504 | 17 | WS | 0.05 |
| CLIMBER-2 | PIK | 2.5 | 2.5 | 4320 | 252 | WS | 2 |
| ECBilt-2 | KNMI | 3 | 2.5 | 38912 | 6144 | SG(2) | 336 |
| CLIO-E-V | Louvain | 3 | 2.5 | 144000 | 6144 | WS | 300 |
| RAS | IAP Moscow | 2.5 | 3 | 7200 | 19200 | WS | 125 |
| MPM | McGill Univ | 2.5 | 1.5 | 648 | 216 | WS | 8 |
| IGSM | MIT | 3 | 2 | 60750 | 216 | WS | 200 |
| MoBidiC | Louvain | 2.5 | 1.5 | 1620 | 72 | WS | 3 |
| PUMA-LSG | MPI Hamburg | 3 | 3 | 28512 | 10240 | Cray | 24 |
| ESCM | U. Victoria (BC) | 3 | 2 | 190000 | ~10000 | SP2 | 240 |
| HADCM3 | Hadley Centre | 3 | 3 | 262656 | 87552 | Cray | 10000 |
| FORTE | SOC/Reading | 3 | 3 | 60750 | 45056 | WS/PC | ~1000 |
| C-GOLDSTEIN | SOC/Univ.Bern | 3 | 2 | 10368 | 1296 | W/S | ~ 1 |
| "Target" | GENIE (UK) | 3 | 3 | 11664 | 6480 | WS | 1 |

## Nature of intermediate complexity models

♦ are invariably (a) **Coarse** , & (b) **Statistical-Dynamical**
  • include explicit dynamics (buoyancy, friction, etc...) for the **mean flow only**
  • do not resolve eddies : treated statistically
  • but include fluxes due to **eddy correlations**
    • which need to be parameterised (turbulence closure)
♦ involve **parameterisation** of eddy fluxes
  • Usually use mixing length &  flux-gradient methods
  • diffusivities (etc)   $K = U* L$,    flux = $K \times$ gradient
  • $U*$ = characteristic **amplitude scale** for velocity fluctuations
  • $L$  = characteristic **spatial scale** of velocity fluctuations (or of the spatial domain)

# 2 and 3D Atmospheric Models

◆ Involve meridional-vertical transports due to

- **radiative forcing** (NB : surface albedo, clouds...)
- **interaction with the land & ocean**
    - by radiation, heating and freshwater fluxes, & winds
- **buoyancy forces** (moist convection)
- **friction**
    - as Rayleigh drag or eddy viscosity (momentum transport)
- **mixing** (lateral & vertical)
    - needs to be very carefully **parameterised**
- **rotation** (which is very important)

# The Atmosphere : Winds
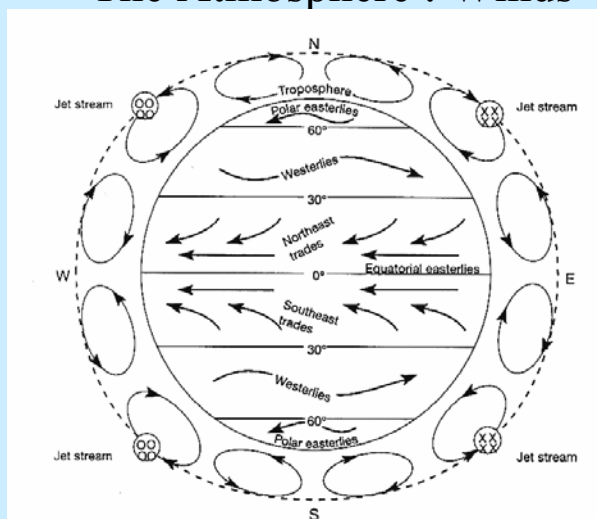


**Figure 3.8** A view of the planet and atmosphere showing locations of major zonal wind directions and jet streams. The jet streams meander from mid to high latitudes in both hemispheres and flow predominately from west to east. The Earth revolves west to east, making one full anti-clockwise revolution about its N–S axis in 24 hours. (After Schneider and Londer, 1989.)

Mackenzie 1995

## Processes included in Statistical-Dynamical atmospheric models

♦ Heat fluxes
   • Sensible (dry) & Latent (moist)
♦ Moisture fluxes (moving freshwater)
   • Evaporation & Precipitation : E-P
♦ Momentum fluxes (zonal winds)
♦ Radiation
   • transmission, absorption, albedo, clouds (explicit)....
♦ Buoyancy & convection
   • leading to mean meridional circulation


## What about Clouds ?

♦ At several (maybe all) levels
♦ Must allow for fractional cloud cover
   • to allow for zonal variations
   • and avoid "blinking" instabilities
♦ usually parameterised in terms of RH
   • as in many GCM's
   • incorporating type vs. altitude correlation
   • but one could model liquid water explicitly...

# CLIMBER-2 : Atmosphere
### Ganopolski et al, Climate Dynamics (2000)
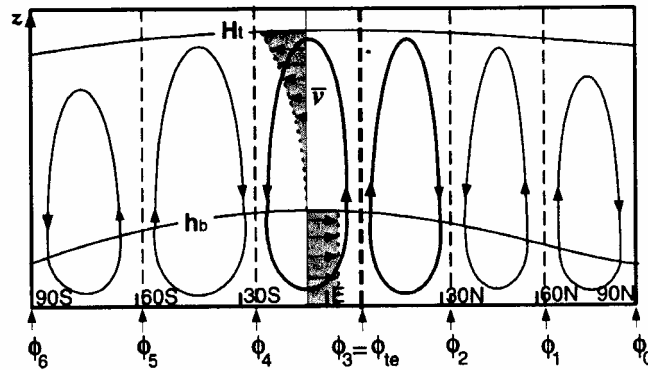


**Fig. 3** Vertical structure of the zonally averaged atmospheric circulation in the model
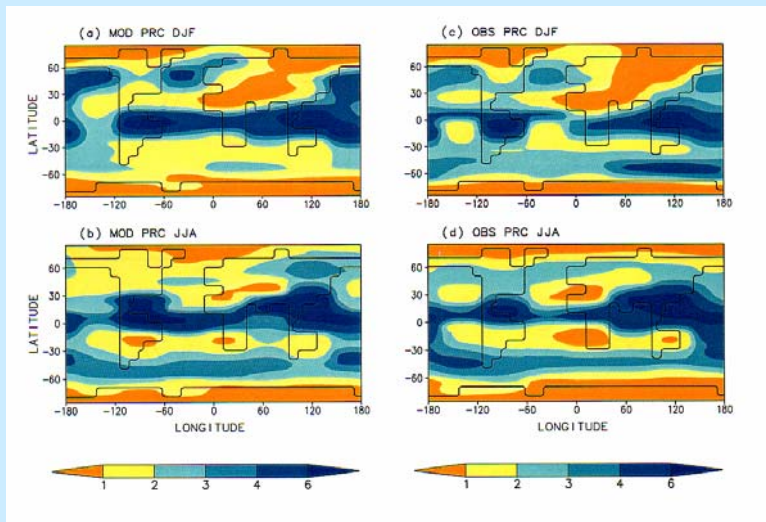
# CLIMBER-2 : Atmospheric circulation
# (zonal wind and meridional overturning)
### Ganopolski et al, Climate Dynamics (2000)
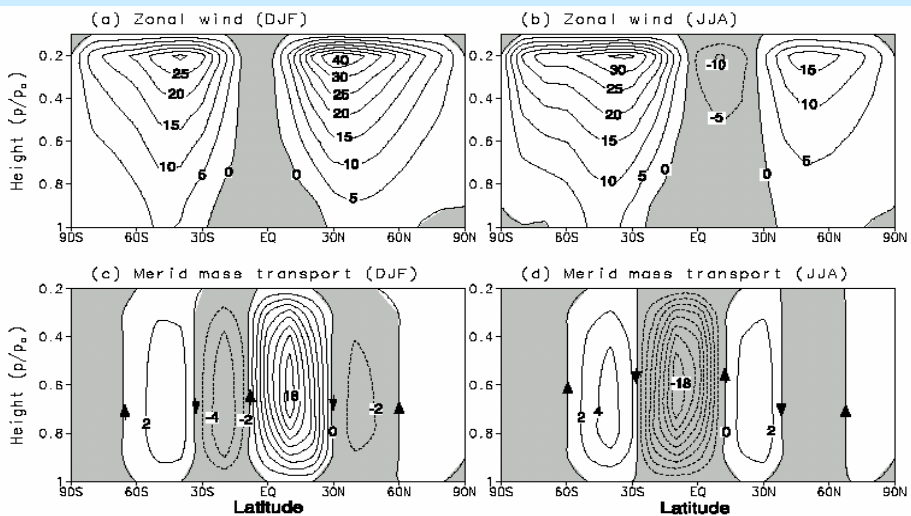
CLIMBER-2 : Precipitation
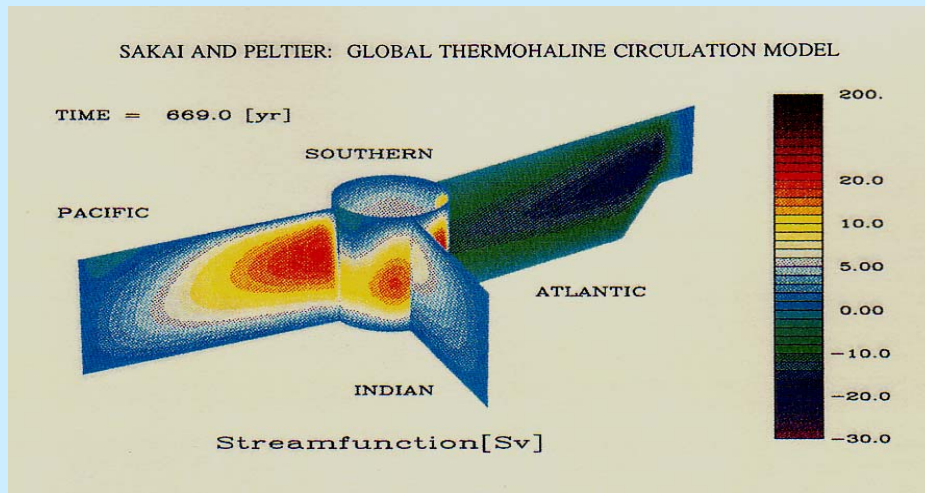Ganopolski et al, Climate Dynamics (2000)

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# 2 and 2.5D Ocean Models

Involve meridional & vertical transports due to

- **surface forcing** (interaction with the atmosphere)
  - by radiation, heating and freshwater fluxes (and winds ?)
- and thus **buoyancy forces**
- balancing **friction**
  - as Rayleigh drag or eddy viscosity
- **mixing** (lateral & diapycnal) : usually specified
- and effects of **rotation** (maybe, somehow)

♦ Examples include...

- Stocker & Wright
- Marotzke et al

# 2.5D Ocean models
## (Stocker, Wright & Mysak 1992)

SAKAI AND PELTIER:  GLOBAL THERMOHALINE CIRCULATION MODEL

TIME = 669.0 [yr]

SOUTHERN

PACIFIC

ATLANTIC

INDIAN

Streamfunction[Sv]

200.

20.0

10.0

5.00

0.00

−10.0

−20.0

−30.0

# CLIMBER-2 : Global Meridional Overturning
## Ganopolski et al, Climate Dynamics (2000)

(c) World ocean

−24

−18

12

6

−15

−9  −6  −3  0

Depth (m)

Latitude
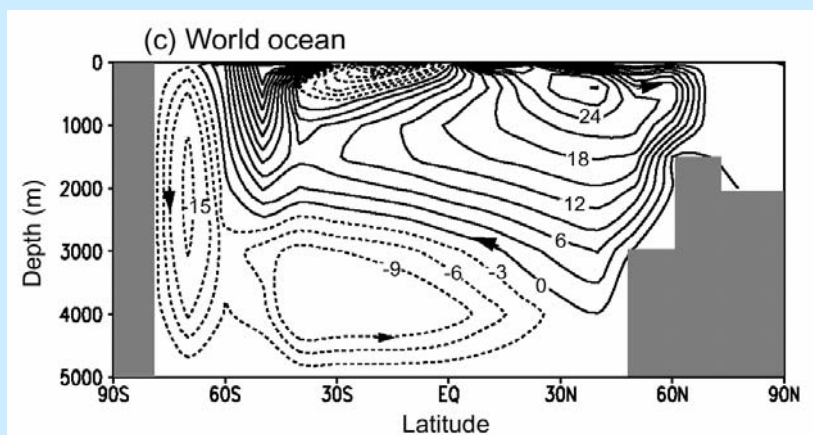
**Suppression of Overturning (Stocker et al)**
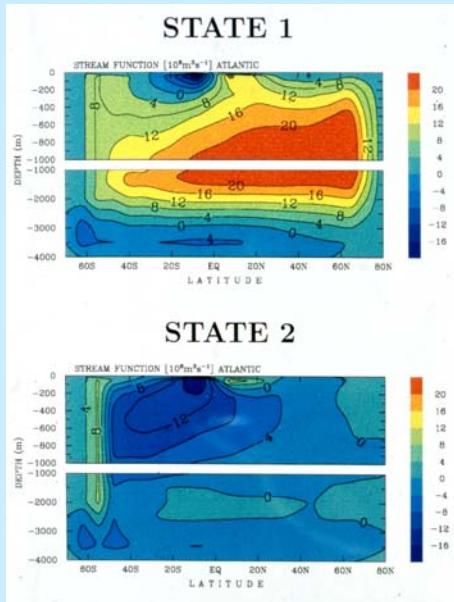
♦ How ??? Freshwater flooding (ice melt)

♦ Natural cycle : ~ bistable ? bipolar see-saw ?

♦ Forcing system with unknown dynamics

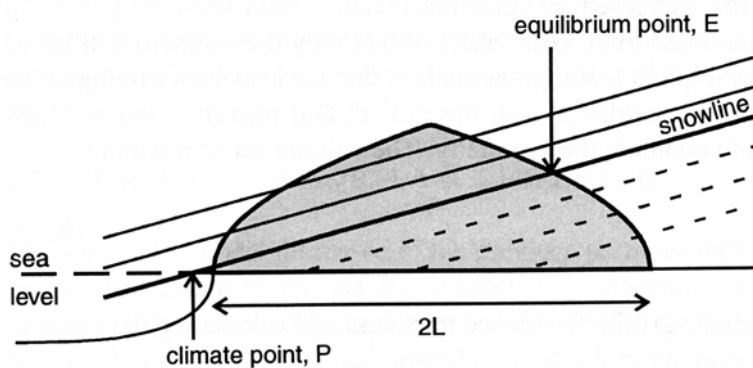♦ Rapidity of transitions (<100 years): Not a distant problem



Multiple states of the Atlantic Thermohaline Circulation
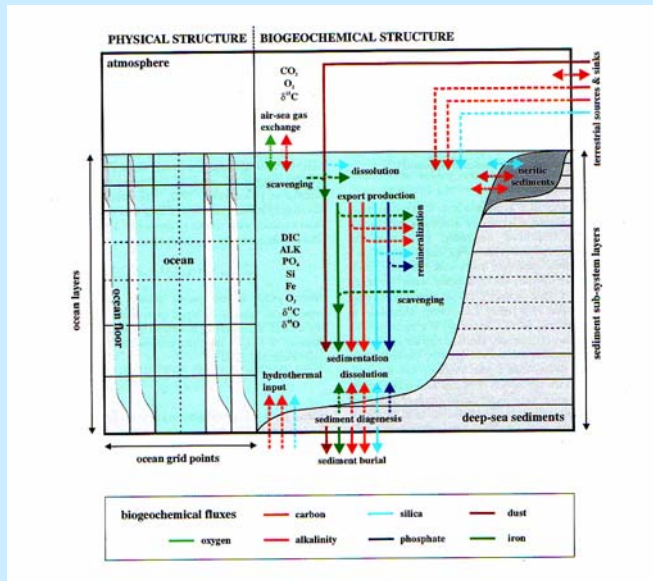(S. Rahmstorf, Climatic Change, 2000)
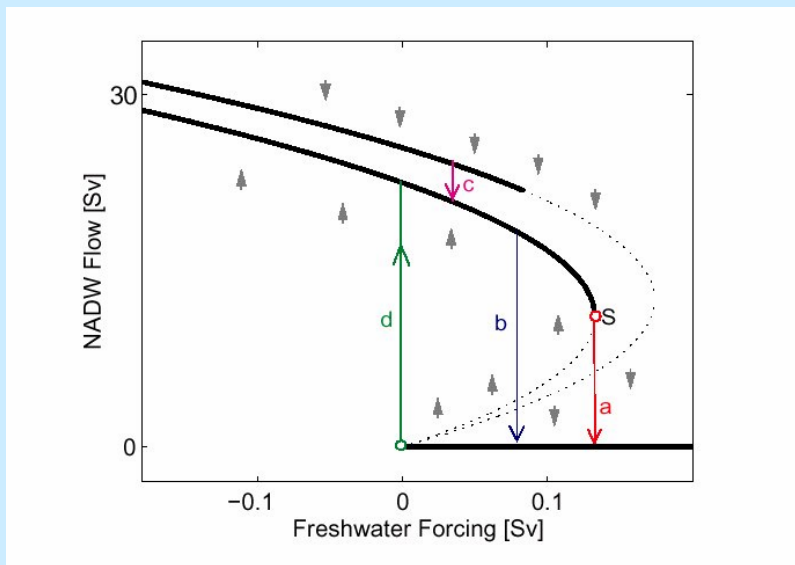
# Land Surface Schemes

♦ Topography
  - elevation & slope
♦ Hydrology
  - soil moisture, runoff
  - drainage basins
♦ Vegetation
  - Carbon cycling
  - albedo...
♦ Ice sheets & glaciers

# Simplified (2D) Ice-sheet models
## (Van der Veen 1999)

# Marine Biogeochemical Processes
(after A. Ridgwell, 2001)



# Why build yet another model ?

♦ We need *Fast & Efficient* climate models
  - To do *long runs* (over many centuries, up to and *beyond* 2100)
    - N.B. : 5,000 year time horizon for exhaustion of fossil fuels and equilibration with marine sediments
  - To do *many runs* (to evaluate sensitivity & uncertainty requires thousands of simulations)
  - To serve as the climate module for an **Integrated Assessment** Model
    - (requires *both* of the above): many realisations
♦ Any climate model needs the *Greenhouse Effect*
  - $\Delta CO_2 \Rightarrow \Delta T$ : Climate Sensitivity
♦ To predict from emissions one needs a *carbon cycle model* (terrestrial and marine)
  - Emissions $\Rightarrow \Delta CO_2$ : (c.f. 1/3 : 1/3 : 1/3)
♦ We need to allow for *surprises…*
  - *E.g. thermohaline shut-down*

# Efficient 3D ocean models

- ♦ MPI Hamburg (LSG)
  - partly implicit numerical scheme
  - neglects acceleration terms
- ♦ Frictional (planetary) geostrophic models
  - solve equations for slow dynamics only
    - neglect acceleration & inertia, include (Rayleigh) friction
  - the "thermocline equations" in realistic geometry
  - Winton & Sarachik (JPO, 1993)
  - Goldstein (Edwards et al, 1998)
  - Edwards & Shepherd (the "Lego-box" model)
    - Climate Dynamics, 2001
    - 1 million years overnight (18 x 18, low resolution)
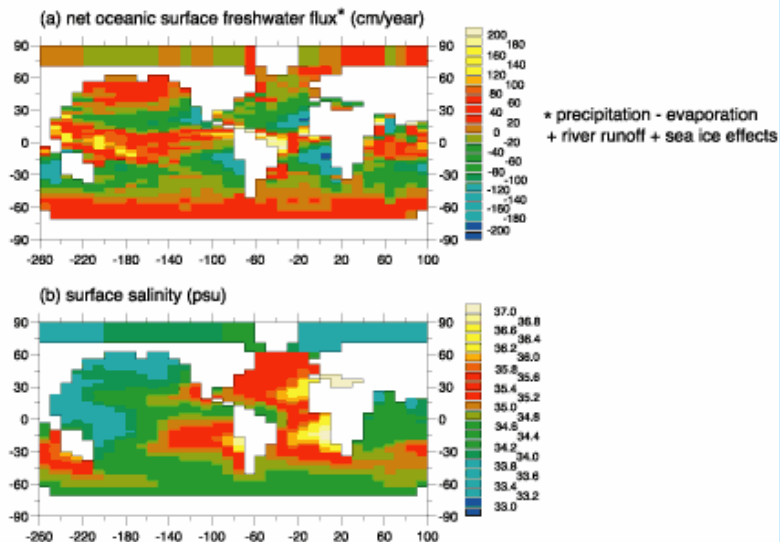
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## C-GOLDSTEIN Version 1:
## Standard configuration

- ♦ realistic world geometry on a 36x36 horizontal grid
  - (~5$^o$ latitude x 10$^o$ longitude)
- ♦ basic 4-catchment runoff scheme
- ♦ smoothed ocean topography (8 ocean depth levels spanning 5000m)
- ♦ asynchronous coupled 2D EMBM atmosphere
  - one ocean time-step (of typically 3.5 days) every 5 atmospheric transport time-steps
- ♦ mixture of explicit (ocean, sea-ice) and implicit (atmosphere) timesteps
- ♦ Isopycnal oceanic mixing scheme
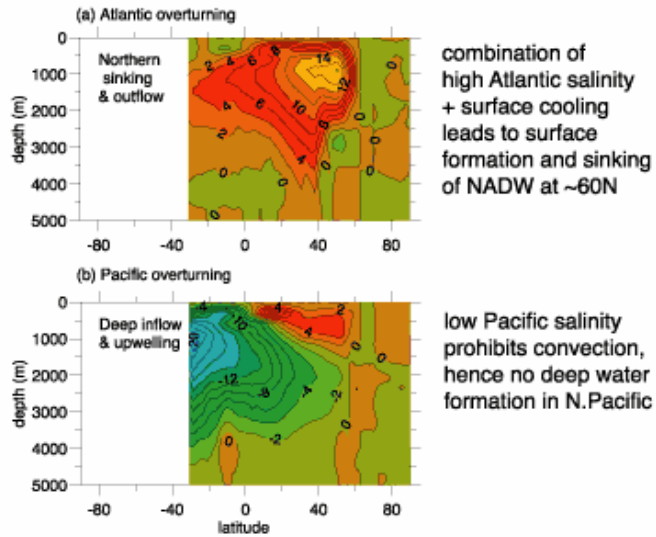- ♦ 2000 years spinup in 1 to 2 hours on fast PC/workstation

A fast ocean-seaice-atmosphere model for Earth System Science, C-GOLDSTEIN* (Bob Marsh & Neil Edwards):

Ocean topography on model grid
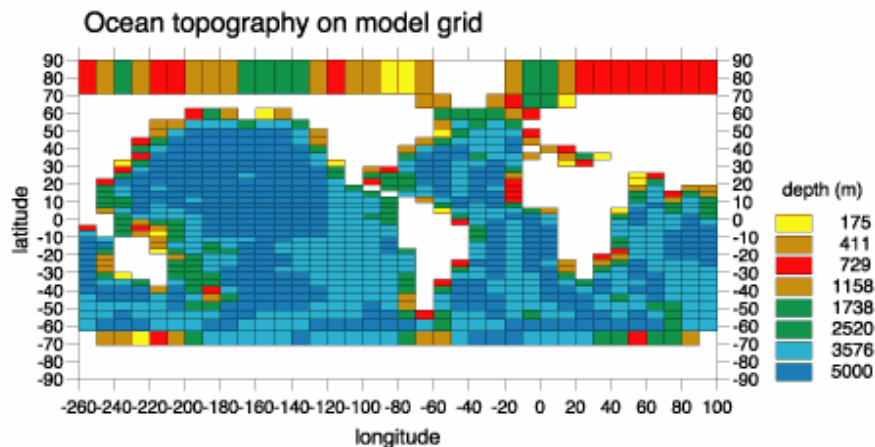


The strength and mode of the "thermohaline circulation" (THC) is sensitive to the global pattern of surface salinity, which is set up by the surface freshwater flux:

(a) net oceanic surface freshwater flux* (cm/year)

* precipitation - evaporation
+ river runoff + sea ice effects

(b) surface salinity (psu)

Under the established pattern of high Atlantic salinity and low Pacific salinity, the model THC is in a "Conveyor Belt" mode:

(a) Atlantic overturning

Northern sinking & outflow

combination of high Atlantic salinity + surface cooling leads to surface formation and sinking of NADW at ~60N

(b) Pacific overturning

Deep inflow & upwelling

low Pacific salinity prohibits convection, hence no deep water formation in N.Pacific

Associated with the Conveyor Belt mode of the THC is strong northward heat transport in the Atlantic, leading to relatively mild climate in northwest Europe

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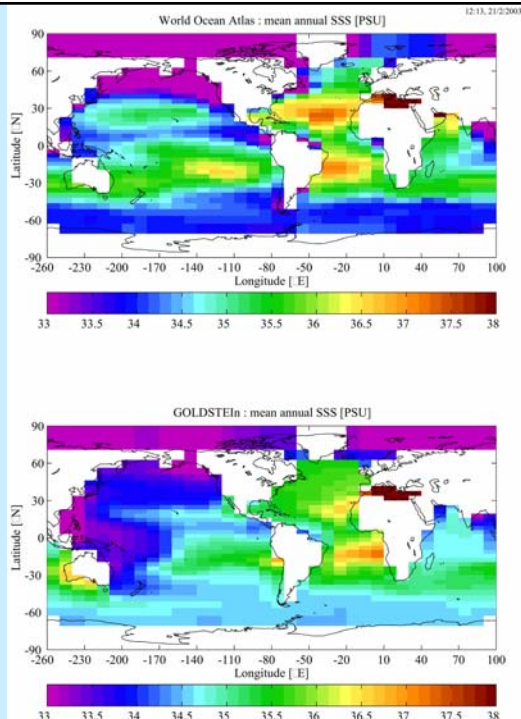
**BC-Goldstein**

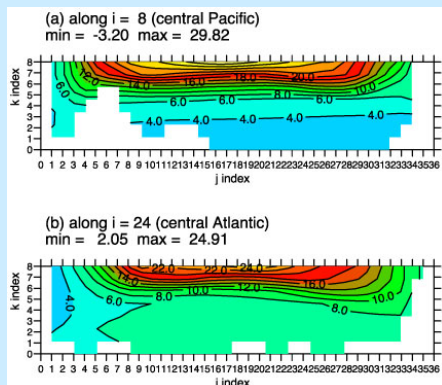Sea surface Temperature

Comparison with observations



World Ocean Atlas : mean annual SST [ C]

GOLDSTEIn : mean annual SST [ C]
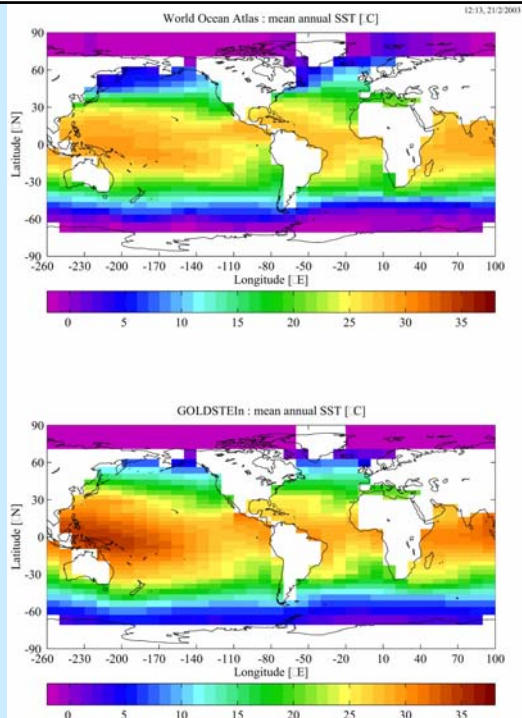
**BC-Goldstein**

Sea surface Salinity
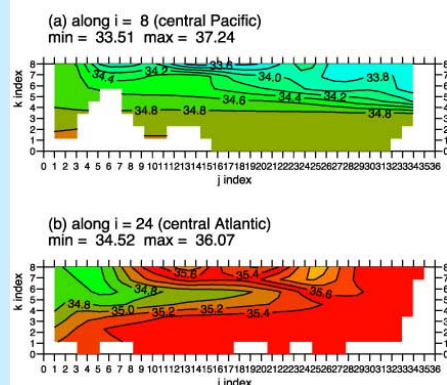
Comparison with observations

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**C-Goldstein:** Water mass properties after 2000-year spinup

**Temperature:**

**Salinity:**
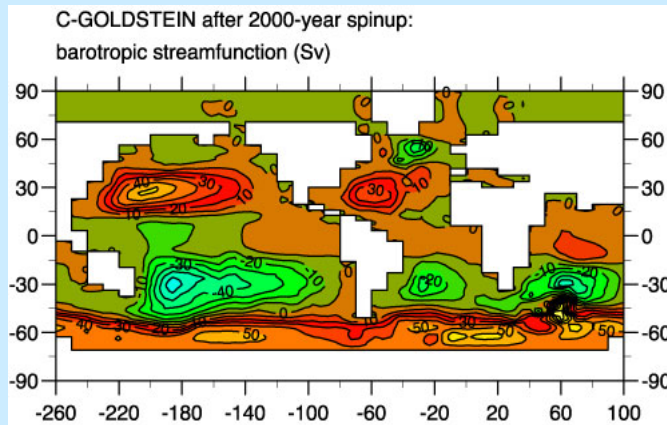
- ♦ strong & sharp thermocline
- ♦ deep Atlantic is too warm and too salty (deep sinking is located too far south)

- ♦ Pacific is fresher than Atlantic
- ♦ salty "NADW" & fresh "AAIW" tongues extend south/north

# C-Goldstein : Wind-driven circulation:



C-GOLDSTEIN after 2000-year spinup:
barotropic streamfunction (Sv)

- ♦ the above solution was obtained using *enhanced wind stress*
- ♦ "standard" model (no enhanced wind stress) has a very weak wind-driven circulation due to the strong drag coefficient needed with real topography



Consider the model ocean and climate response to the most extreme meltwater pulse in terms of surface freshening, MOT weakening and regional cooling:
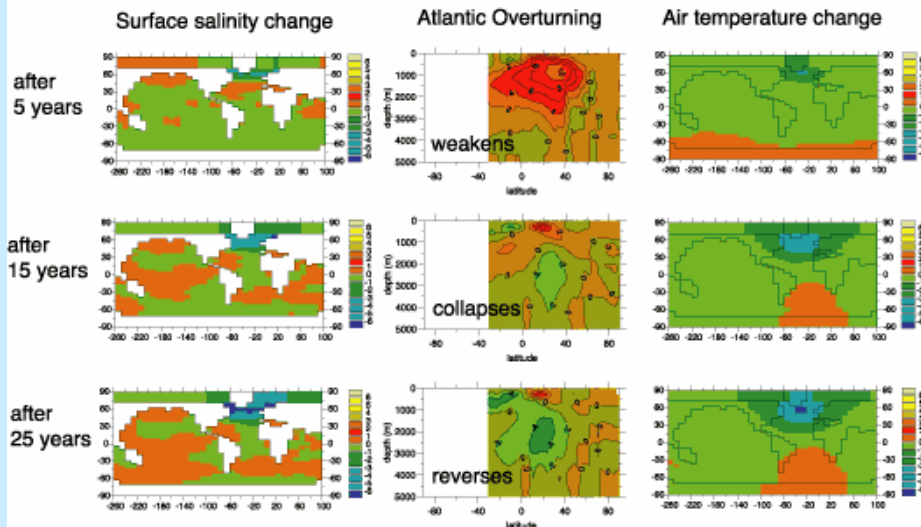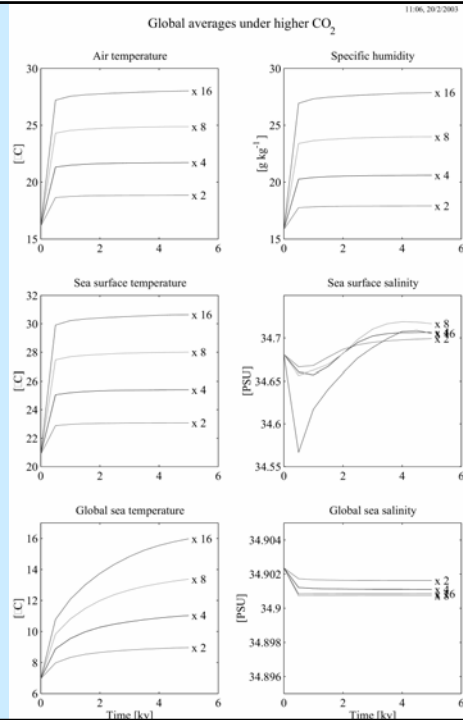
C-Goldstein : Global Warming Simulation (2 x $CO_2$)
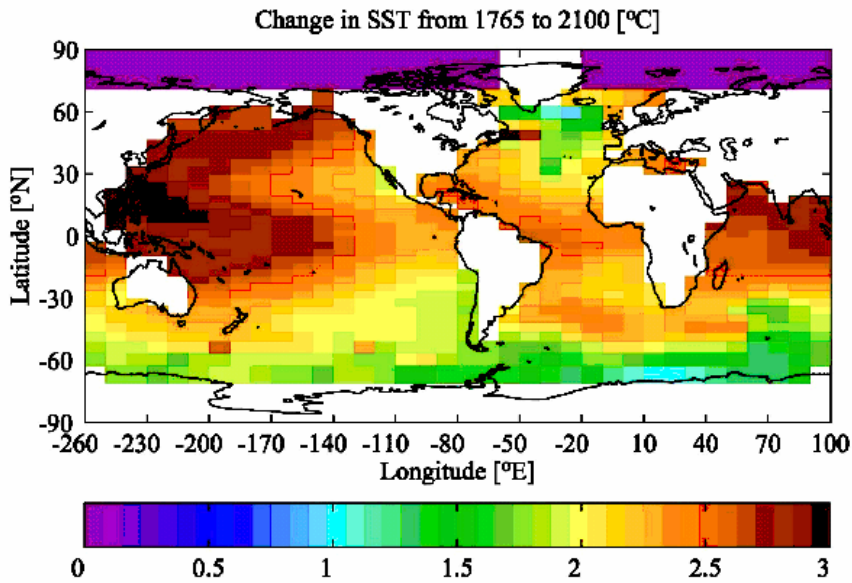


**C-Goldstein**

5000 year Global Warming simulations for 2, 4, 8 and 16 times $CO_2$

## Multiple THC equilibria: Background

♦ Paleodata suggest at least three stable equilibria of the THC (and Atlantic climate) in the recent past: Holocene; Heinrich; Glacial

♦ Evidence that the THC "jumps" between such equilibria is found in "hysteresis loops" of THC strength vs. forcing - obtained in "slow" climate models by slowly varying an anomalous freshwater flux over selected regions of the North Atlantic
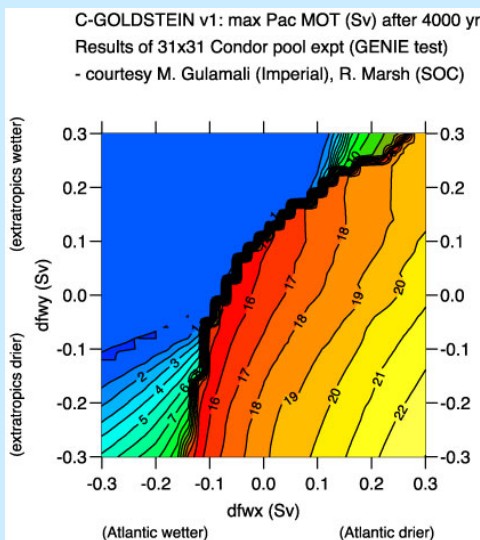
CLIMBER-2 hysteresis loops:

Under present climate          Under Glacial climate
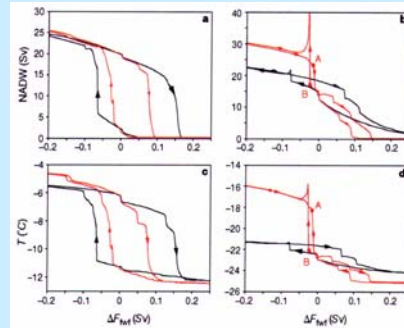


black = anomalous flux applied 50-70°N
red = anomalous flux applied 20-50°N

(from Ganopolski & Rahmstorf 2001)

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## Using Condor pools to investigate equilibrium Atlantic overturning rate in dfwx-dfwy space



C-GOLDSTEIN v1: max Pac MOT (Sv) after 4000 yr
Results of 31x31 Condor pool expt (GENIE test)
- courtesy M. Gulamali (Imperial), R. Marsh (SOC)

♦ 961 runs (3,844,000 model years!) took ~3 days, resolving at dfwx, dfwy intervals of just 0.02 Sv

♦ Two states of THC are apparent: ON (towards bottom right corner), OFF (towards top left corner)

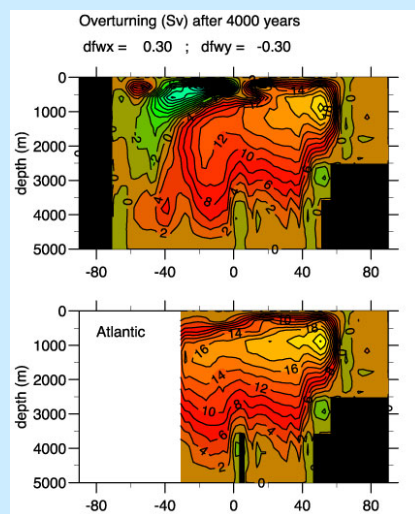♦ Present day overturning (at dfwx = 0, dfwy = 0) lies not far from the "cliff" between these states!

# Meridional overturning circulation streamfunctions corresponding to two extremes of freshwater forcing

### Weak FW forcing (S sinking)



Overturning (Sv) after 4000 years
dfwx = -0.30 ; dfwy = 0.30
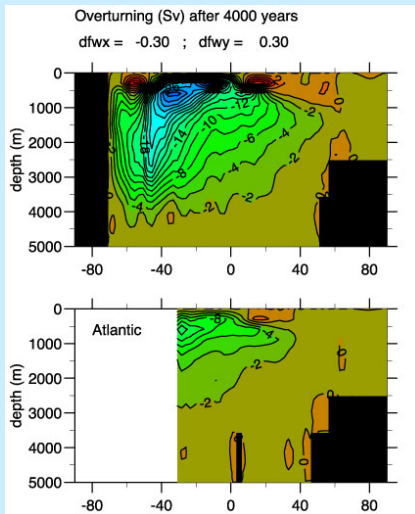
Atlantic

### Strong FW forcing (N sinking)



Overturning (Sv) after 4000 years
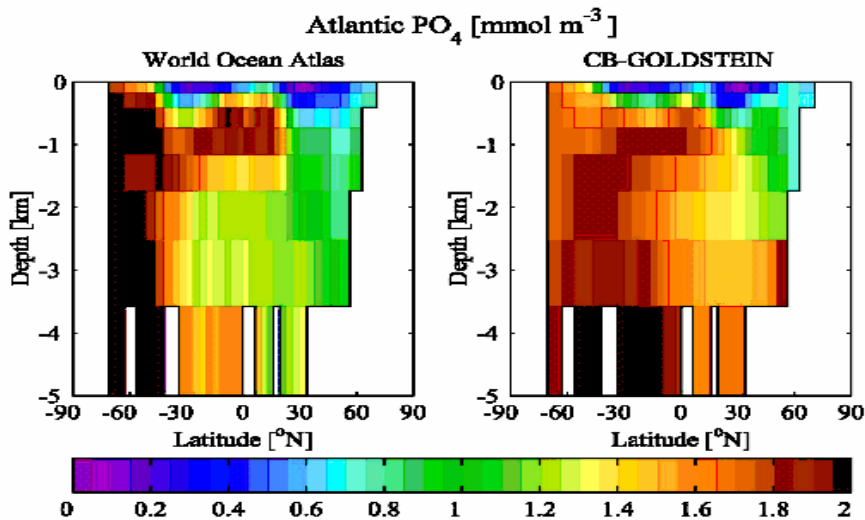dfwx = 0.30 ; dfwy = -0.30

Atlantic

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# C-Goldstein: Sensitivity of the thermohaline circulation and climate to enhanced freshwater forcing

Change of surface air temperature after 25 years of a 1 Sv meltwater pulse, located in the Atlantic zone at 50-70°N.



change in model air temperature (°C)
min = -4.83  max = 0.19
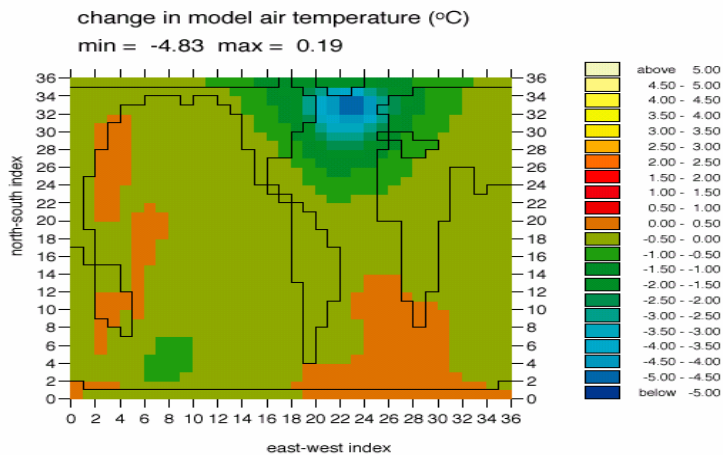
# Biogeochemistry & Nutrients (PO$_4$)
## Comparison of model with observations



Atlantic PO$_4$ [mmol m$^{-3}$]

World Ocean Atlas — CB-GOLDSTEIN

# BC-Goldstein

Air-sea pCO2 differences modelled using phosphate depleting "biology"

Comparison with observations



Takahashi (1997) ΔpCO$_2$ [ppm]

CB-GOLDSTEIN ΔpCO$_2$ [ppm]
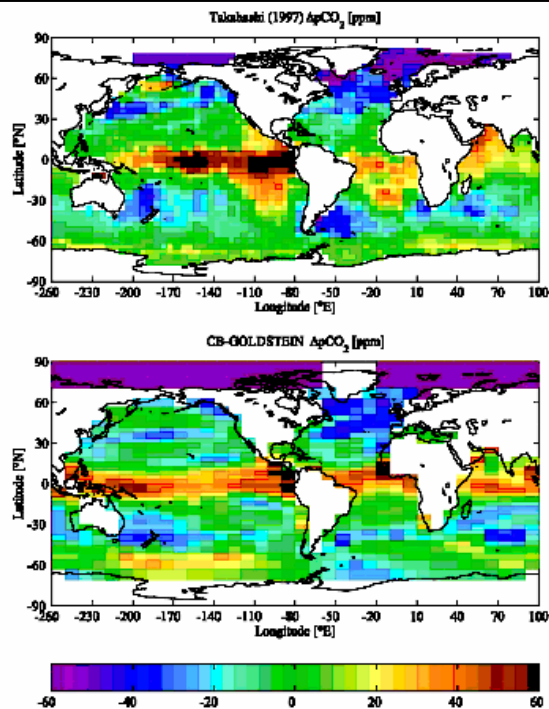
# Variability & Predictability

- ◆ The Earth's Climate System apparently exhibits **Multiple quasi-stable states**
  - • presumably due to positive feedbacks
- ◆ and **Quasi-periodic behaviour**
  - • damped natural modes, paced by external forcing ?
- ◆ On all time scales (?) from **seasons to aeons**
- ◆ We need efficient ESM's
  - • to **explore parameter-space**
  - • to run decent-sized **ensembles,** to establish variability, and the extent of predictability
  - • for proper **interpretation of palaeo-climate proxies**
- ◆ We need a diverse **spectrum of efficient models**, also to allow for **inter-comparison & replication**

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# Where next ?   We need to...

- ◆ **Play !!**
  - • to allow for accidental discoveries
  - • this requires over-night runs (at most)
- ◆ **run ensembles** and/or **explore parameter space**
  - • this needs hundreds to thousands of runs
- ◆ **extend integration times** to >30 kyr
  - • with moderate resolution models
- ◆ ∴ **develop faster schemes** (with longer time-steps)
- ◆ **"populate the spectrum"** of models
  - • in both **structure** & in **resolution**
  - • **inter-compare** (up/down the spectrum)
- ◆ promote **scalability** and **modularity**
- ◆ develop new & better **parameterisations...**

# Parameterisation

♦ is a **high order intellectual activity**

♦ requires **"asymptotic credibility"**

♦ preferably based on **"sound science"**

♦ we could/should
  - **"cascade" parameterisations** up/down the spectrum
  - use **statistical representations** of sub-grid scale distributions
    - work with percentile values within cells
    - for hydrology, topography, clouds, ice, vegetation...

# Conclusions

♦ **Earth System Models of Intermediate Complexity**
  - are necessary, desirable, and very useful tools
    - complementary to, and not "second best" to GCM's
  - are the **only** option (for the next decade or so)...
  - for **testing** our (seriously incomplete) understanding of **natural variations of climate**
  - because these occur **mainly** on palaeo (multi-millennial and longer) time-scales
  - EMIC's are still at an early stage of development, and are certainly **capable of major improvement**
  - We need more efficient representations of **fluid processes**, and more effective **parameterisations**

♦ Eventually, we need to use *data assimilation*, and *inverse modelling methods*, on palaeo-datasets...

## Modelling & Philosophy

♦ **"Science may be described as the art of oversimplification: the art of discerning what we may with advantage omit."**

- Karl Popper, "The Open Universe", Hutchinson, London (1982)


*"Man has lost the capacity to foresee and to forestall. He will end by destroying the Earth"*

Albert Schweitzer, quoted by Rachel Carson, in her dedication of "Silent Spring", (1962)